

WATER IMPACT ANALYSIS METHODOLOGY FOR AIRCRAFT¹

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Abstract

This paper describes an effort that focuses on the development of a crash modeling and simulation approach utilizing both a nonlinear finite-element code (MSC/DYTRAN) and a hybrid impact code (DRI/KRASH) to demonstrate the potential for airframe water impact analysis in the development of crash design criteria and concepts. In the Phase I effort results from ditching tests of a scale model VTOL aircraft are compared with analysis results from both MSC/DYTRAN and DRI/KRASH.

The research is now in Phase II of a Small Business Innovation Research (SBIR) program sponsored by the U.S. Navy, with participation by the Federal Aviation Administration (FAA). During this phase, full scale water impact tests will be conducted for the first time, along with water impact crash simulations and correlation.. One of the primary objectives of the program is to develop analytical tools that can be used to facilitate the process of showing compliance with current civil and military ditching requirements with a decreasing dependence on expensive scale model ditching tests.

The paper presents correlation between analyses and ditching test results for accelerations and contact surface pressures. The paper also describes how the analytical tools developed under the SBIR will be applicable to civil transport category aircraft.

Introduction

Because the U. S. Navy conducts extensive aircraft operations overwater, they need to ensure that their aircraft provide effective crash protection not only for ground impacts, but also for both controlled ditchings and uncontrolled crashes into water. The facts listed below have motivated the U. S. Navy to conduct research into advancing water impact crash protection.

- The U.S. Navy experiences more aircraft crashes into water than any other flying organization worldwide. Some Navy aircraft experience more than 75 % of their crashes into water.
- Experience has shown that during severe but survivable water impacts, dynamic pressures can be significantly higher than the static design requirements.
- The structural response and load transfer mechanism for impacts on water or soft soil is very different than for impacts on hard surfaces.

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In addition to the U.S. Navy, there is a need on the part of civil helicopter manufacturers and users to improve safety during water impact accidents. When compared to research conducted by the U.S. Army, NASA, and the FAA on airframe behavior during hard surface impacts, little water impact research has been done in recent times. Other than minimal ditching requirements, the U.S. Navy and the FAA have no identifiable water impact design criteria and no acceptable water impact methodology with which to address the water impact scenarios.

To better understand the water impact phenomenon, and to eventually increase survival potential in water crashes, the Naval Air Warfare Center, Aircraft Division sponsored a SBIR effort to investigate water impact dynamics relevant to DOD, DOT and industry. This program, which is also supported by the FAA, has the following long-range objectives:

- Develop a viable validated methodology with which to evaluate rotary-wing aircraft structural performance in ditchings and severe but survivable water impacts.
- Establish crash design criteria that will ensure a level of safety consistent with potentially survivable water impact scenarios.
- Consider potential design concepts that will enhance airframe resistance to water impacts.

Methodology

The approach adopted to meet the long-range goals of the U.S. Navy is to use two types of models: hybrid (intermediate) and finite element (detailed). This approach is described in Reference 1. The hybrid terminology refers to the ability to use available test or other data as input along with internal calculation of structural parameters. A pure finite element model (FEM) program generally does not allow the user to input external test data as an alternative to an internal calculation of such data. These two concepts offer different advantages and disadvantages.

TABLE 1. COMBINED FEM/HYBRID APPROACH

<u>FEM Advantages</u> <ul style="list-style-type: none"> • Detail design/condition oriented • Local interaction/attachment behavior • Design accuracy • Specific component application 	<u>FEM Disadvantages</u> <ul style="list-style-type: none"> • Time-intensive setup and run times • Does not accept test/other data as input • Difficult to approximate behavior • Limited aircraft application/impact scenarios
<u>Hybrid Advantages</u> <ul style="list-style-type: none"> • Model setup and fast run times • Global analysis oriented • Accepts test and other data as input • Preliminary design tool and overall behavior • Defines critical parameters and conditions • System application versatility 	<u>Hybrid Disadvantages</u> <ul style="list-style-type: none"> • Approximate solutions • Not detail element oriented • Limited internal criteria • Not stress-strain oriented • Not local behavior oriented • Not component design oriented

The approach presented in this paper utilizes computer codes that provide the greatest opportunity to achieve the stated goals. Since neither of the available hybrid nor the pure FEM codes have demonstrated a capability to meet all the requirements stated earlier, the combination of FEM/hybrid modeling will, in the long run, be the most advantageous.

The use of both FEM and hybrid analyses as illustrated in Figure 1 provides for the ability to perform complementary procedures, thus maximizing the strengths of each approach, while minimizing the weakness of each. The FEM offers detailed design analysis potential, particularly for local regions or airframe segments. The hybrid modeling offers a more practical cost-efficient and versatile analysis technique more closely associated with preliminary design, global analysis, and parametric tradeoff studies.

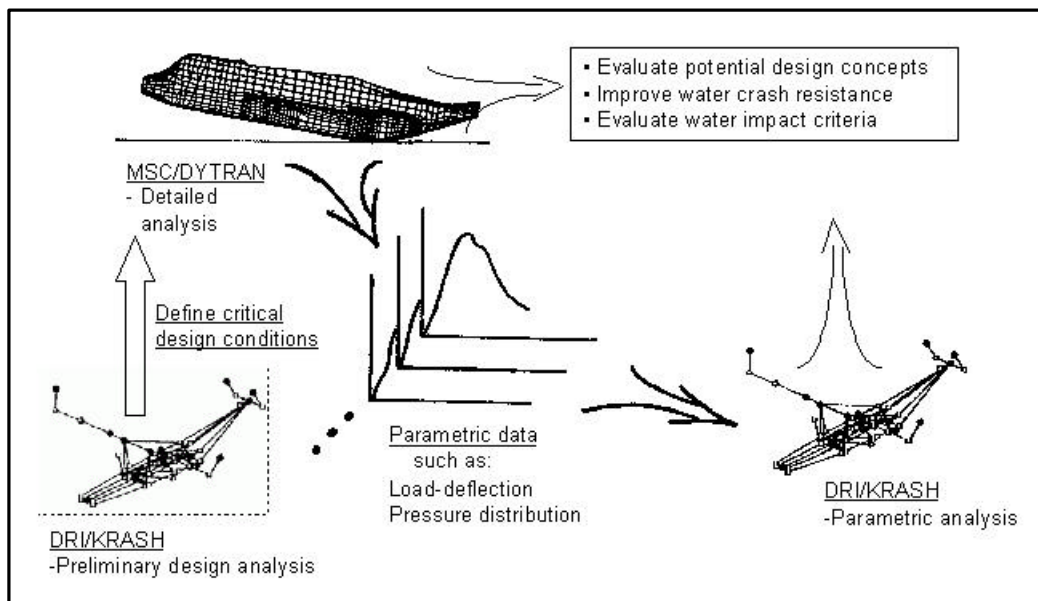


FIGURE 1. COMBINED FEM/HYBRID APPROACH FLOWCHART

A number of nonlinear, transient dynamic analysis programs can fit into the detailed finite element concept. Since the SBIR effort does not allow a detailed assessment of all codes, MSC/DYTRAN and DRI/KRASH were chosen as the representative state-of-the-art detailed and hybrid codes, respectively, to prove concept feasibility.

Description of MSC/DYTRAN

MSC/DYTRAN[†] is a general-purpose finite element code that uses the explicit formulation of the finite-element method to treat significant nonlinear problems with geometric and material nonlinearity. It contains both Lagrangian and Eulerian processors. The Lagrangian processor uses a control mass approach and is primarily applicable to structural problems. The Eulerian processor uses a control volume approach and is used mainly for fluid

[†]MSC/DYTRAN is a registered trademark of the MacNeal-Schwendler Corporation, Los Angeles, California.

problems. The two processors can be coupled in two different ways (ALE and general coupling), depending on the nature of the problem.

The MSC/DYTRAN structural model can be made up of isotropic or orthotropic shell and/or solid elements with elastic-plastic yield/failure criteria or composite failure models. It is possible in MSC/DYTRAN to model the structure as Lagrangian and have it surrounded by an Eulerian mesh. The space above the water can be filled with a void or with air. It is also possible to model the fluid with Lagrangian solid elements having no yield strength. Depending on the objectives of the model, each approach contains advantages and disadvantages. Thus, as with any methodology, the user's understanding of the code's strengths and weaknesses and user's experience are essential.

Description of DRI/KRASH

The DRI/KRASH™ code evolved from the KRASH public domain version. Reference 2 contains a description of KRASH features and applications and is representative of the numerous KRASH-related publications. Reference 3 describes the latest DRI/KRASH program. Some of the DRI/KRASH features that are not available in the public domain KRASH are summarized as follows:

- PC and workstation portability
- Variable integration & variable plastic hinge
- Metric system-6 options
- Occupant head strike analysis (HIC & SIC)
- Soft soil module and preprocessor
- Comprehensive oleo-pneumatic landing gear module
- Beam, crush spring, and terrain property card options
- Water impact module (see Table 2)
- Increased Size; 1200 DOF, 200 Masses, 400 beams, 500 nonlinear elements, 100 crush springs, 100 hydrodynamic lift and 100 drag surfaces
- Compatible pre- and post-processing software available

Summary of Results

In the SBIR Phase I effort, which is described in Reference 1, the technical merit and feasibility of the methodology was demonstrated. This paper presents a summary of those results. A more complete presentation of the Phase I results is shown in Reference 1. A MSC/DYTRAN model of an aircraft, for which scale model test data exists for a series of impact scenarios, was utilized. In addition DRI/KRASH models for the same scale model test article were utilized in addition to two other rotary wing aircraft representations. The latter two were representative of known accident conditions.

Since water impact test data was available from Reference 4 for a scale model of a tiltrotor at 42,600 lb GW (Figure 2), this configuration was selected for water impact analysis under calm sea-state

™ DRI/KRASH is a registered trademark of Dynamic Response, Inc of Sherman Oaks, California

conditions. The fuselage of the aircraft was modeled with MSC/DYTRAN using 2977 rigid planar elements as shown in Figure 3. The wing and nacelles were not represented since test data indicated the

TABLE 2. DRI/KRASH WATER IMPACT FEATURES

Modeling Surfaces

- Lifting, drag, and vertical penetration surfaces
- 100 primary and 100 secondary coupled lifting and drag surfaces each (total of 400 surfaces)
- Multiple point attachments to drag surfaces
- Design and failure load criteria
- Pressure calculations - vary with changing area of penetration
- Multiple shape provisions for lifting and penetration surfaces; 9 shapes - equivalent disk or displaced volume approximation
- Overall RMS pressure calculation for reference

Sea State

- Wave height, length and propagation
- Wind magnitude and direction
- Perpendicular face landing on up-slope, down slope, crest, or trough
- Parallel landing on crest, trough or lateral slope

Input data options

- Scale factor for shape, dynamic effects, FEM data, test data
- Load-deflection data coupled with structure deformation
- Provisions for available calibrated hydrodynamic data

Output Data - Standard

- Hydrodynamic force related energy dissipation and distribution
- Tabular summary of hydrodynamic surfaces - forces, pressures, penetration
- Summary of surface failures - surface type, location and time of occurrence

Optional output data

- Lifting and drag surface penetration, force and pressure time histories



FIGURE 2. SCALE MODEL WATER IMPACT TEST

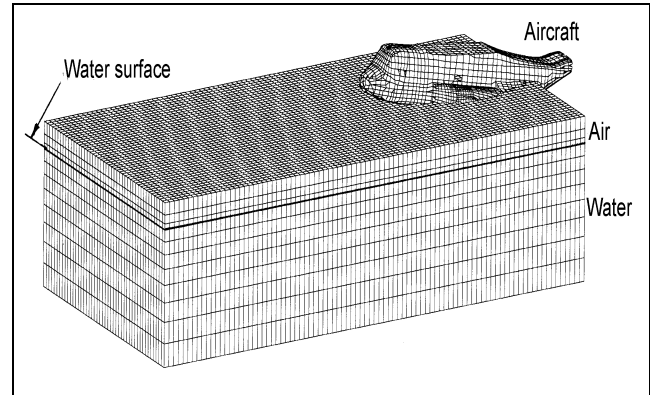


FIGURE 3. MSC/DYTRAN MODEL OF AIRCRAFT FLUID

peak accelerations occurred while the aircraft is still in a nose-up pitched attitude and thus prior to water contact with the nacelles. The fluid was modeled initially using 43,200 Lagrangian solid elements with no yield strength that covered an area of 600 inches long by 300 inches wide and 240 inches deep. Since, for the condition analyzed, the aircraft had no yaw or roll attitude and rate, a symmetric half model of the Lagrangian mesh was used to reduce the computation time. Modeling fluids with Lagrangian solid elements significantly reduces the computational time required by simplifying calculations for fluid-structure interaction; however, Lagrangian elements lose some physical fidelity available with Eulerian elements. In addition, the Lagrangian mesh length of 600 inches proved to be inadequate to capture the full sequence of water impact. Furthermore, contour mapping of fuselage underside pressures is currently available only for Eulerian meshes. Therefore, subsequent modeling used 32,400 Eulerian elements to represent the water and 10,800 Eulerian elements to model the air above the water mesh. The total Eulerian mesh covered an area of 1200 inches long by 600 inches wide and 100 inches deep. The fluid mesh in the area of initial impact had elements each with a size of 13 inches long by 13 inches wide and 10 inches deep. The Eulerian air mesh up to 3 ft. height above the water surface was used to maintain general coupling between the Lagrangian fuselage and the Eulerian water after rebound and secondary recontact.

The results of the MSC/DYTRAN analysis at 30 knots forward velocity, 6 ft/sec sink rate, 67-percent rotor lift and 10-degree nose-up attitude using the Eulerian fluid mesh show the aircraft reaching a nearly level attitude at approximately 0.50 seconds, which is consistent with the reported test results. Initial impact at time 0.005 seconds resulted in a peak pressure of 21.0 psig at fuselage station (FS) 550. At time 0.025 seconds, a peak fluid pressure of 22.0 psig is noted in the analysis at FS 535.5 versus approximately 23.1 psig measured in test at FS 532. Thereafter, the peak fluid pressure continues to decline to approximately 4 to 6 psig as the aircraft levels off.

At the aircraft CG, the analysis indicates a peak vertical deceleration of 2.5 g (Figure 4) was reached versus test results of 1.9 g at FS 412 near the CG. Correspondingly, the longitudinal deceleration peaks at 0.35 g versus 0.7 g measured in test. As the aircraft sinks into the water and drags forward, the nose down (negative) pitching moment of the aircraft CG continues to increase until the aircraft starts to level off and areas ahead of FS 550 and longitudinally closer to the aircraft CG impact the water at approximately 0.50 seconds.

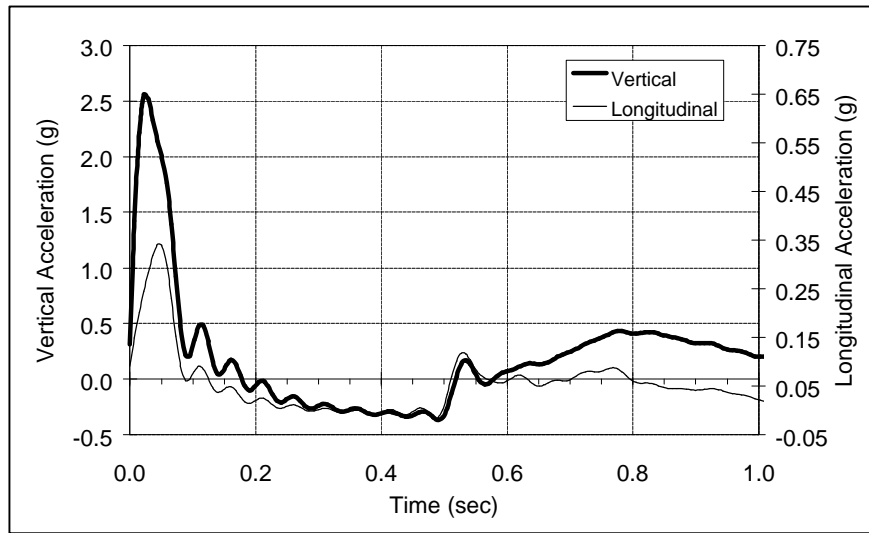


FIGURE 4. FUSELAGE CG ACCELERATION

DRI/KRASH hybrid modeling used currently available KRASH models of a 9,000 lb, a 20,000 lb rotorcraft, and a 42,600 lb VTOL aircraft. Each model was modified to accommodate the hybrid modeling requirements for representing hydrodynamic forces. The objective of these analyses are to demonstrate the advantages of the hybrid approach, i.e.,

- 1) analysis of the entire impact scenario (beyond initial impact), which is not well suited for detailed FEM,
- 2) versatility of application to different aircraft configurations and a wide range of impact conditions, and
- 3) utilization of available test or FEM data.

For the purposes of subsequent discussion, the DRI/KRASH hybrid models are noted in Table 3 and shown in Figure 5. Their weight representations, model sizes, simulation and computer run times are noted.

TABLE 3. DRI/KRASH MODEL SIZES

Parameter Numbers (a)	TYPE 1	TYPE 2	TYPE 3
Aircraft Weight, lb.	9000	20000	42600
No. Masses	24	68	21
Beams	32	116	38
Node Points	14	40	34
Hydrodynamic Lift Surfaces	8	24	6
Hydrodynamic Drag Surfaces	8	24	6
DRI's(b)	0	4	0
Simulation Time (sec)	0.120	0.200	0.500
Computer CPU runtime (c)	0.54	3.0	1.5

(a) Full Model

(b) Dynamic Response Index spinal injury elements

(c) Minutes on Pentium 333 MHz PC

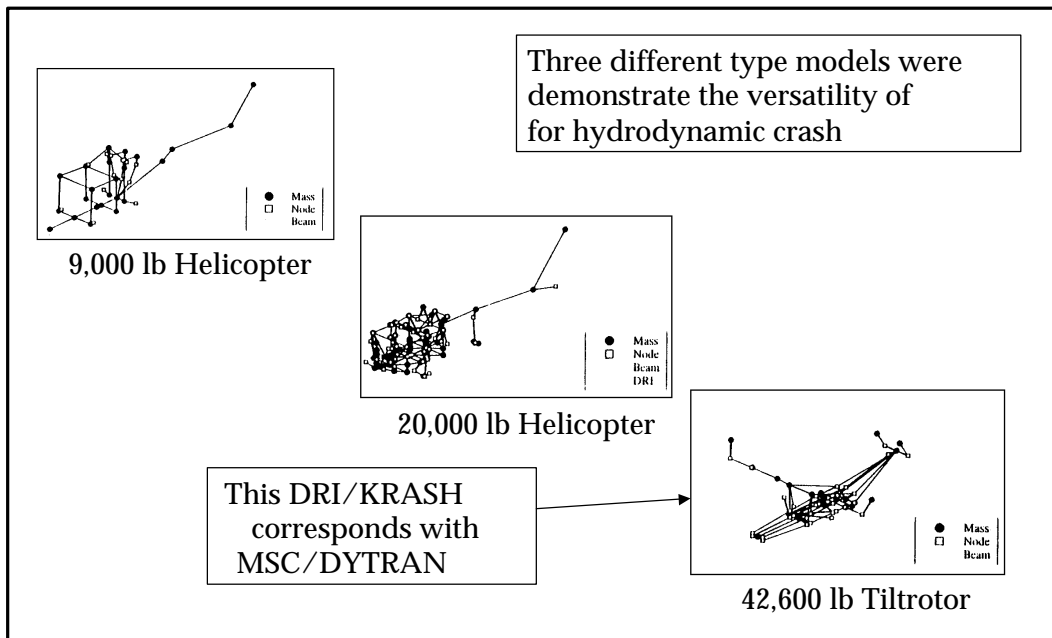


FIGURE 5. DRI/KRASH HYBRID MODELS

The Type 1 model simulation is representative of a rotorcraft accident with gear extended and a high forward velocity (169 ft/sec), low sink speed (5 ft/sec), nose-up (+3-degree) impact attitude, which has demonstrated reasonable results when compared to the available accident data. Simulating this condition, which resulted in severe damage and nose-over behavior, allows the engineer to evaluate a number of possible design changes or operational variations.

The Type 2 model simulation is representative of a severe 50 ft/sec sink speed, 10-degree nose-down pitch accident in which extensive airframe damage and fatalities occurred. Analysis of this condition enables the engineer to evaluate the effect upon occupant survivability that selected design changes or operational procedures could have.

Type 3 Hybrid Model Analysis - Ditching Condition Analysis. The DRI/KRASH hybrid analysis was performed for the 42,600 lb aircraft for the same ditching conditions as noted earlier for the MSC/DYTRAN analysis. The results for the forward CG case indicate the following:

- The peak responses (see Table 4) occur within 0.080 seconds after impact and are between 2.3 g (analysis) and 2.6 g (test) at the aft end, 1.3 g and 2.5 g (analysis) versus 1.9 g (test) at the mid fuselage and between 1.0 g to 2.8 g (analysis) versus 1.5 g to 1.7 g (test) at the forward fuselage
- The peak longitudinal acceleration is observed in the test to be approximately 0.75 g and to occur around 0.090 sec after impact. The peak longitudinal acceleration (analysis) occurs at around 0.080 sec after impact and varies from 0.52 g (at a FS 342 mass) to between 0.9 to 1.0 g at locations comparable to where the vertical direction accelerations were measured.

TABLE 4. SUMMARY OF PEAK ACCELERATION COMPARISONS

Location	Analysis	Test
Vertical Acceleration - g at time (sec)		
FS 552 - 576	2.3 (0.020)	2.6 (0.027)
	2.3 (0.020)	2.5 (0.080)
	1.7 (0.120)	1.9 (0.150)
FS 412 - 417	2.5 (0.020)	1.9 (0.027)
	1.3 (0.080)	1.9 (0.072)
FS 217	1.0 (0.050)	1.5 (0.030)
	1.4 (0.160)	1.6 (0.072)
	2.8 (0.210)	1.7 (0.250)
Longitudinal Acceleration - g at time (sec)		
CG	0.52 (0.080)	0.75 (0.090)

- The peak pressures (see Table 5) are in good agreement at the five locations in proximity to the measured locations (Reference 3).

TABLE 5. SUMMARY OF PEAK PRESSURE COMPARISONS

	Peak pressure - psi at time (sec)		Initial contact of FS after impact - sec	
Location (FS)	Analysis	Test	Analysis	Test
552 - 576	2.6 (0.050)	3.0 (0.018)	0.000	0.000
	-	-7.0 (0.072)	-	-
532	16.2 (0.070)	18.0 (0.050)	0.020	0.033
	16.4 (0.100)	-	-	-
486	19.7 (0.390)	20.0 (0.136)	0.110	0.108
380 - 386	17.2 (0.490)	14.0 (0.430)	0.410	0.380

- The analysis indicates that the aircraft reaches a 1.57-degree nose-up attitude at 0.500 seconds after impact from the initial 10 degree nose-up attitude. At this time, the pitch attitude is still decreasing although at a substantially reduced rate. The test results indicate that the aircraft held attitude at touchdown, then trimmed slowly to a level attitude before settling and slowing down, which

supports the sequence of peak pressure readings. The attitude of the aircraft in the analysis also supports the peak pressure sequence and is in agreement with the test data.

The comparison of MSC/DYTRAN and DRI/KRASH results, as well as the Osprey VTOL aircraft scale model ditching test results, are noted in Figure 6 and 7 and table 6.

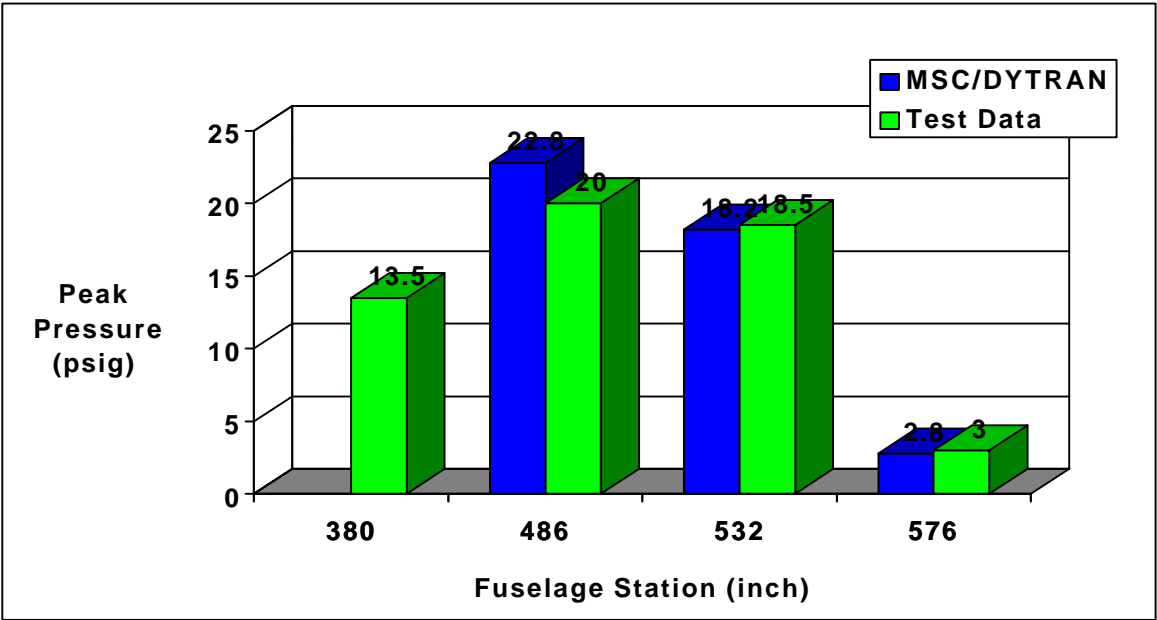


FIGURE 6. COMPARISON OF PRESSURE RESULTS

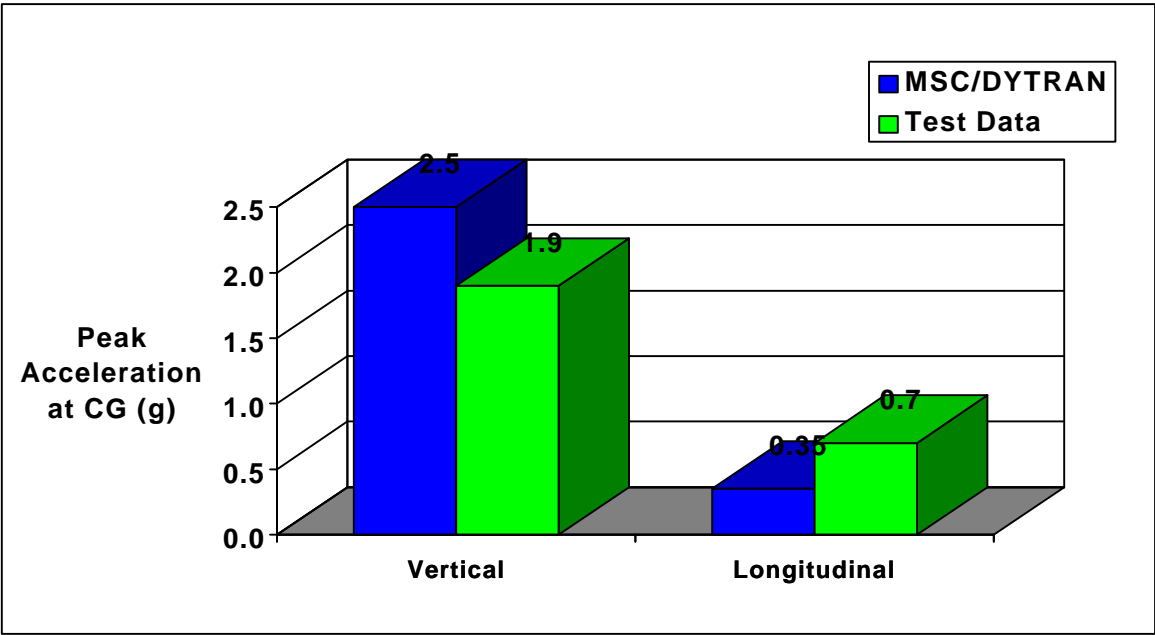


FIGURE 7. COMPARISON OF ACCELERATION RESULTS

TABLE 6. SUMMARY OF ANALYSIS AND SCALE MODEL DITCHING TEST RESULTS

	DRI/KRASH	MSC/ DYTRAN	Test Data (Ref. 3)
Pressures-psi at (time-sec)			
FS552-576	-2.0 to + 2.6 (0.050)	--	+3.0 to -7.0 (0.018-.072)
FS532	16.2 to 16.4 (0.070-0.100)	18.2 (0.005)	18-19 (0.050)
FS486	19.7 (0.390)	22.8 (0.100)	20.0 (0.136)
FS380-386	17.2 (0.490)	--	14.0 (0.430)
Acceleration - g at CG			
Vertical	1.3 - 2.5 (0.020-0.080)	2.5 (0.055)	1.9 (0.027-0.072)
Longitudinal	0.5 (0.080)	0.35 (0.085)	0.7 (0.080-0.090)

The Technical Merit and Feasibility Assessment

The combined FEM/hybrid methodology to accurately represent helicopter airframe behavior for water impact scenarios and survivable envelopes has been demonstrated to be feasible. The assessment included the following:

1. A total of 12 different and distinct impact and ditching test conditions were analyzed with both the FEM and hybrid analyses, as noted in Figure 8, along with accident data impact envelopes. These conditions are part of 32 separate analyses performed in the SBIR Phase I effort.

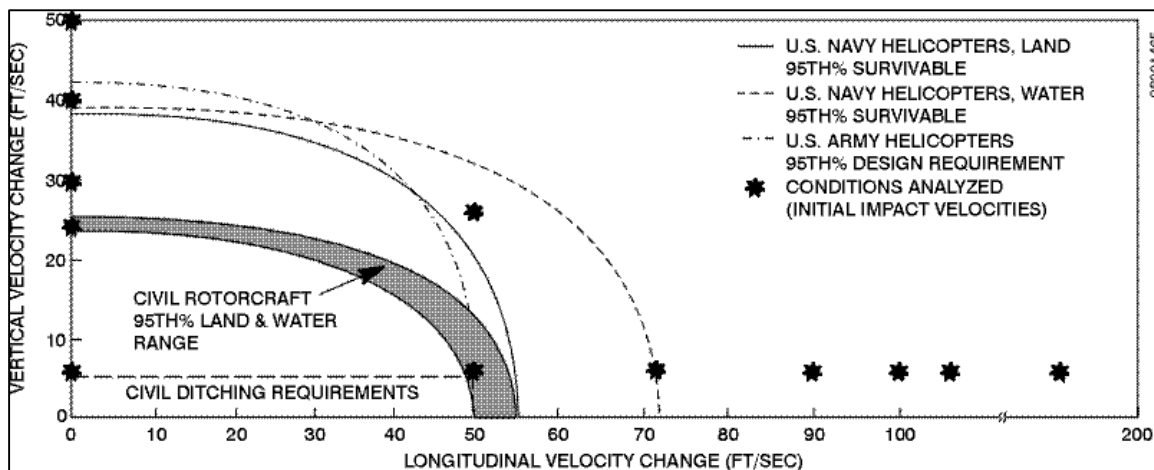


FIGURE 8. IMPACT CONDITIONS ANALYZED

2. The 42,600-lb GW rotary-wing aircraft was modeled and analyzed using MSC/DYTRAN for several impact conditions representing:
 - Ditching test conditions that provided data with which to compare analytical results
 - Impact conditions from which response forces and trends could be obtained
3. The 42,600-lb GW rotary-wing aircraft was modeled and analyzed using DRI/KRASH for a scale model ditching test condition with calm sea; forward and aft CG positions.
4. A 9,000-lb GW rotary-wing aircraft was modeled and analyzed using DRI/KRASH for several parametric variations, including the effect on responses and aircraft behavior of:
 - Forward velocity (72, 122, 169 ft/sec)
 - Lift versus no lift
 - Impact shape and design criteria
 - Sea state
 - Parallel and perpendicular wave landings
 - Symmetrical versus unsymmetrical landings
 - Landing gear extended versus landing gear retracted
5. A 20,000-lb GW rotary-wing aircraft was modeled and analyzed using DRI/KRASH for several parameter variations including the effect on responses and airframe behavior of:
 - Aircraft underside contour shape, configuration, and size
 - Energy absorbing seats on occupant injury potential
 - Sink speed (24, 30, 40, 50 ft/sec)
 - Pitch attitude (± 10 degree)

The technical merit of this approach is best established by the reasonably good correlation of most fundamental parameters such as kinematic behavior in terms of pressure and acceleration trends with available test data.

Current SBIR Phase II Effort

The team of DRI, BHTI and Simula Technologies Inc. recently initiated the SBIR Phase II effort under sponsorship of NAWCAD and in participation with the FAA. The Phase II effort is a 2 year program with the following planned major tasks:

- Development of both DRI/KRASH and MSC/DYTRAN models of the UH-1H helicopter
- Full scale water impact testing of a UH-1H helicopter configuration in both a vertical-only impact and a combined vertical-longitudinal impact
- Pre-test simulation of UH-1H water impact conditions and correlation with test, and post-test applications
- Modeling and simulation of a V-22 Osprey full scale ditching tests and water impacts using both DRI/KRASH and MSC/DYTRAN

- Development of compliance procedures for ditching certification utilizing analytical methodology
- Development of design guidelines, design improvements and design criteria for water impacts

The UH-1H helicopter was chosen as the test article for several reasons, including availability of design data, model data and test articles. The initial simulation/correlation effort is the first step in validating analysis methodology for many future potential applications. The Phase II effort is applicable to the DoD, DoT and industry, as well as to many potential aircraft and water impact related events, including;

- Rotary wing aircraft; military and civil
- Fixed wing aircraft; military and civil, commuters and transport category aircraft
- Design criteria and concepts
- Ditching procedures
- Flotation, occupant survival, survival time, evacuation, flotation systems

The initial Phase II effort is directed toward utilizing the existing UH-1H NASTRAN model to upgrade or develop existing and new UH-1H DRI/KRASH and MSC/DYTRAN models. For example the original UH-1H KRASH model developed in 1972 was a full model consisting of 31 masses and 37 beam elements, and there was no MSC/DYTRAN model. The current revised KRASH UH-1H helicopter model, shown in Figure 9, is a half model which when expanded to full size consists of

- 132 masses
- 290 beams
- 32 each - lower contour hydrodynamic pressure surfaces, secondary floor hydrodynamic impact surfaces and hydrodynamic drag surfaces

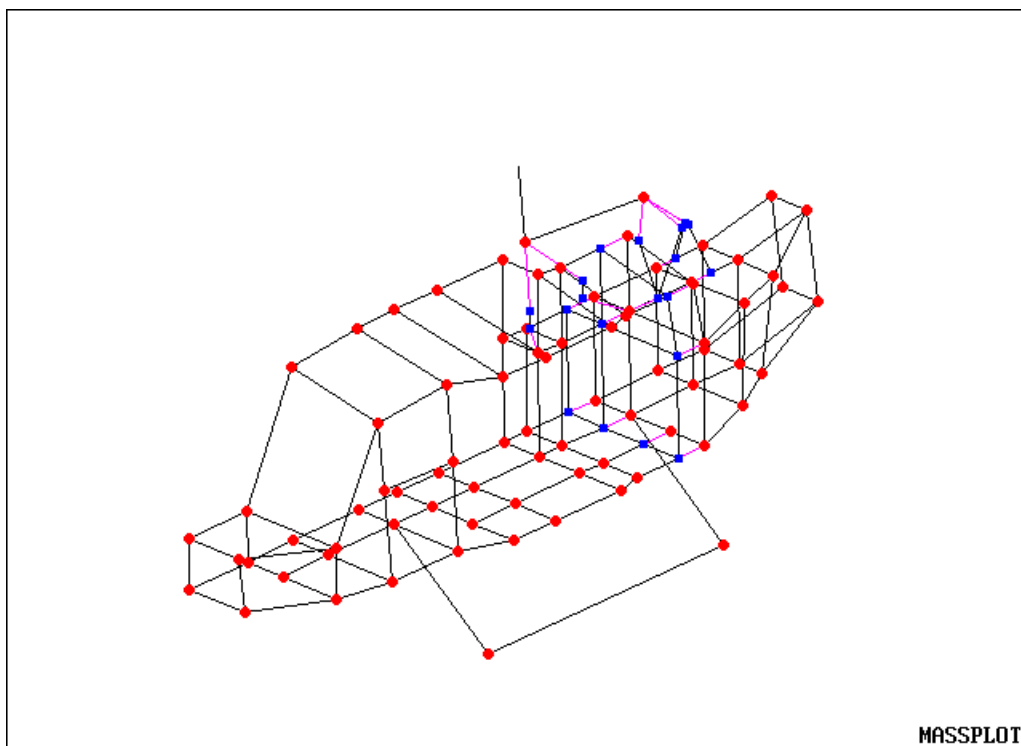


FIGURE 9. DRI/KRASH UH-1H MODEL

The current MSC/DYTRAN UH-1H helicopter model is shown in Figure 10. The structural model consists of:

- 1424 Grid points (GRID)
- 76 bars (CBAR)
- 77 triangular (CTRIA3) elements
- 1558 quad (CQUAD4) elements

In addition the water mesh and air gap models consist of Eulerian solid (CHEXA) elements. The meshes, which are currently sized for a vertical impact, are:

- Water; 8 layers- 100 inches deep, 250 inches long, and 200 inches wide
- Air; 5 layers- 25 inches deep, 250 inches long, and 200 inches wide

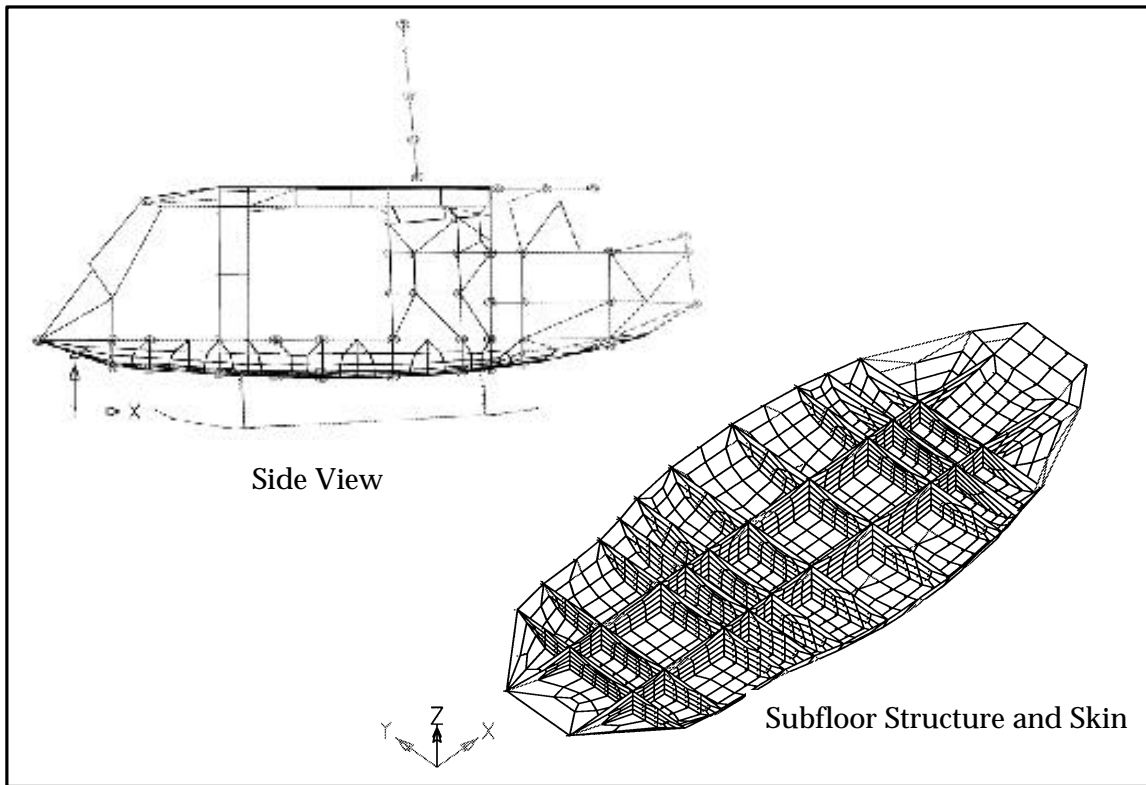


FIGURE 10. MSC/DYTRAN UH-1H MODEL

Conclusions

The research completed to date has shown that a combined FEM/Hybrid analytical modeling approach for predicting and analyzing aircraft crash response in water impact is feasible and merits further development. Results from a SBIR Phase I effort demonstrate that the combined modeling approach maximizes the benefits of two distinctly different, but complementary methodologies. The results also show the accuracy and versatility of the approach. A brief description has been provided which outlines the current SBIR Phase II effort. Expanded validation of the methodology with full scale test data will provide the DoD, DoT and industry with an opportunity to develop water impact design criteria for both rotary-wing and fixed-wing aircraft, as well as develop compliance procedures for ditching and flotation systems. The methodology goes beyond water impact and can easily be applicable for all terrain considerations, including rigid ground and soft soil.

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